SOLAR DRYER PERFORMANCE STUDY OF SOME CROPS (MINT, OKRA AND GRAPES) II - COMPATIBILITY OF SOLAR DRYING BEHAVIOR WITH MATHEMATICAL MODELS FOR THIN LAYER DRYING PROCESS

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ABSTRACT

In this work, the sun drying behavior of some plants as mint, okra and grapes was investigated. Drying experiments were conducted in Zagazig, Sharkia. During the drying experiments, the solar radiation ranged from 95 to 900 W/m^2, the air velocity from 5 to 12 m/s. The solar radiation energy is maximum at midday and minimum at evening in the day of experiment. Moreover, the temperature of ambient air ranged from 36 to 39 °c. Mean relative humidity just above surface of the plants varied between 23 % and 29 %. The drying data were fitted to six different mathematical models. Among the models, the results of statistical analyses undertaken on these models for mint, okra and grapes are given in tables 2, 3 and 4, respectively. The models were evaluated based on X^2, MBE and RMSE. For mint leaves, the Modified Page (I) model was the best descriptive model, it was determined that $X^2 = 2.52x10^{-3}$, MBE=0.0188 and RMSE = 0.77611. For okra, the Newton model was the best descriptive model, it was determined that $X^2 = 3.47x10^{-3}$, MBE=-0.012 and RMSE = 0.051. For grapes, the Wang and Singh model was the best descriptive model, it was determined that X^2= 1.1x10-3, MBE=-0.02823 and RMSE = 0.116417.

***Keywords:** solar drying; mathematical modeling; mint; okra; grapes.*

INTRODUCTION

Drying of fruit and vegetables is one of the oldest forms of food preservation methods known to man and is the most important process for preserving food since it has a great effect on the quality of the dried products. The major objective in drying agricultural products is the reduction of the moisture content to a level which allows safe storage

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over an extended period. Also, it brings about substantial reduction in weight and volume, minimizing packaging, storage and transportation costs. In spite of many disadvantages, sun drying is still practiced in many places throughout the world such as tropical and subtropical countries. Solar energy is an important alternative source of energy and preferred to other energy sources because it is abundant, inexhaustible and non-pollutant. Also, it is renewable, cheap and environmental friendly ***(Basunia and Abe 2001).*** Thin layer equations describe the drying phenomena in a united way, regardless of the controlling mechanism. They have been used to estimate drying times of several products and to generalize drying curves. In the development of thin layer drying models for agricultural products, generally the moisture content of the material at any time after it has been subjected to a constant relative humidity and temperature conditions is measured and correlated to the drying parameters ***(Midilli et al.2002; Togrul and Pehlivan 2004).*** Many researches on the mathematical modeling and experimental studies have been conducted on the thin layer drying processes of various vegetables, fruits and agro based products such as bay leaves ***(Gu¨nhan et al. 2005)***, hazelnut ***(O¨zdemir and Devres 1999)***, green pepper, green bean and squash ***(Yaldiz and Ertekin 2001)***, apricot ***(Sarsilmaz et al. 2000); (Togrul and Pehlivan 2003)***, green chilli ***(Hossain and Bala 2002)***, pistachio ***(Midilli and Kucuk 2003)***, potato ***(Akpinar et al. 2003a)***, apple ***(Akpinar et al. 2003)***, pumpkin ***(Akpinar et al. 2003b)***, red pepper ***(Akpinar et al. 2003)***, eggplant ***(Ertekin and Yaldiz 2004)***, carrot ***(Doymaz 2004)***, fig ***(Doymaz 2005)***, citrus uranium leaves ***(Ait et al. 2005)***, rosehip ***(Erenturk et al. 2004)***, kiwi ***(Simal et al. 2005). Zomorodian et al. (2009)*** In order to find the best mathematical model for sultana grapes thin layer solar drying of the indirect and mixed-mode type, a cabinet solar dryer was employed. The Modified Page and Page models showed the best curve fitting results for the experimental moisture ratio (MR) values for indirect and mixed-mode type, respectively. The drying parameter effects, namely air velocity and temperature, were established by introducing the best fit correlation equations for the constants involved in the selected mathematical model. ***Doymaz and Pala (2002)*** studied the applicability of several forms of

thin layer drying equations to drying grape. The experiments were proceeded using a convective dryer in single layer with air at 60°c. Grapes were surface treated by different dipping solutions on hot air drying. The drying rate of grapes was modeled by the Page and exponential equations. They found that the values of R^2 obtained from the Page equations are higher than those attained from the exponential equation. The R^2 values of the Page equation vary between 0.995 and 0.999, and between 0.973 and 0.995 for the exponential equation. Both equations could represent the correlation between the moisture and drying time. ***Azzouz et al. (2002)*** studied thin layer characteristics of grapes. The temperature of the air is normally adjusted to be between 50 to 70 °c, the air humidity from 10 to 30 % and the velocity of the drying air from 1.0 to 2.3 m/s. The result showed that, under the experimental conditions cited above the constant "k" and "n" of Page equation were correlated with the variables of drying. The variable of drying, (drying air temperature, relative humidity and velocity), values of the constant "k" were affected by the temperature of the air. Consequently the air velocity and the initial water content of product have a considerable effect on the constant "u". Similar results were obtained by ***Pangavhane et al. (2000).***
The main objectives of this study are to:

- Study the drying kinetics of mint, okra and grapes under solar drying system.
- Fit the drying curves with 6 mathematical models and find the best descriptive models.
- Calculate the diffusivity coefficients of mint, okra and grapes.

MATERIALS AND METHODS

The solar drying experiments were carried out during the period of summer 2013, 2014 in Zagazig, Sharkia. Each test started at 10:00 am and continued till 18:00 pm. Mint ,okra and grapes were distributed uniformly in a thin layer in the sample tray. Figure (1 and 2) shows a schematic diagram and the test solar dryer. In the experiments, weather temperature, relative humidity, wind speed and solar radiation, air temperature and humidity inside the dryer and moisture content of samples were recorded at 60 min intervals. The experiments were repeated three times for obtaining more accurate results.

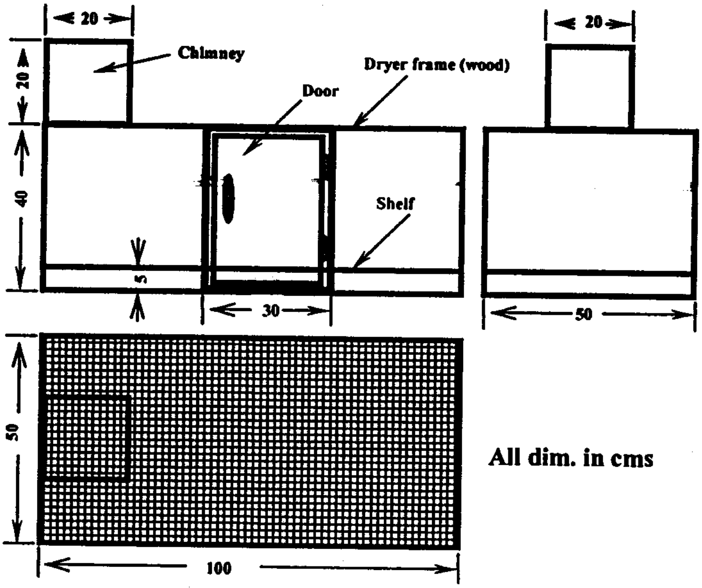


Figure (1): Schematic diagram of the solar dryer.

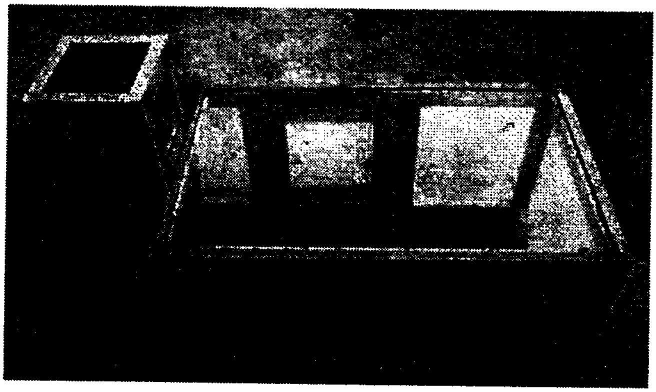


Figure (2): The solar dryer.

Measurements

Weight of samples was measure using electric balance (accuracy 0.01 g and maximum weight 3000 g). Solar radiation and temperature of ambient air were measured by "Watchdog" weather station model 900 ET. The Weather station measures wind speed (0-175 mph) ± 5%, wind direction (2° increments) ± 7°, temperature (-30° : 100° c), relative humidity (20-100%) ± 3%, rainfall (0.01-0.25 cm) ± 2% and solar radiation (1- 1250 W/m^2).Air temperature inside the dryer was recorded at different positions using thermometers with accuracy of 1°c with maximum of 100°c and with calibrated thermocouples connected to a multi channel digital display with an accuracy of 0.05°c. Moisture content was measured using the electric oven. Humidity was measured using Klima Guard digital thermo-hygrometer, the range for relative humidity form (1 to 99 %) with accuracy of (±3.5 %). Air velocity was measured using the anemometer model, the range for air velocity form (0 to 45 m/s) with accuracy of (±0.3 m/s).

Mathematical modeling

The moisture ratio (MR) was calculated using the following equation:

$MR = (M_t - M_f)/(M_0 - M_f)$,

Where: M_o and M_f are initial and final moisture contents (d.b) and M_t is the moisture content at the drying time period (min).

For mathematical models with thin layer drying equations in table (1) were tested to select the best model for describing the drying curve equation of mint, okra and grapes during drying process. Regression analyses were done by using the statistical routine. The coefficient of correlation (r) was one of the primary criterions for selecting the best equation to de-fine the solar drying curves ***(Kassem, 1998; O' Callaghan et al., 1971; Werma et al., 1985).*** In addition to r, the various statistical parameters such as; reduced chi-square (X^2), mean bias error (MBE) and root mean square error (RMSE) were used to determine the quality of the fit. These parameters can be calculated as following:

$$X^2 = \frac{\sum_{i=1}^{n}\left(MR_{\exp,i} - MR_{pre,i}\right)^2}{N-n}$$

$$MBE = \frac{1}{N}\sum_{i=1}^{N}\left(MR_{pre,i} - MR_{\exp,i}\right)$$

$$RMSE = \left[\frac{1}{N}\sum_{i=1}^{n}\left(MR_{pre,i} - MR_{\exp,i}\right)^2\right]^{\frac{1}{2}}$$

where $MR_{exp,i}$: is the stands for the excremental moisture ratio found in any measurement, $MR_{pre,i}$: the predicted moisture ratio for this measurement, N: the number of observations and n: is the number constants.

Table(1) Mathematical models given by various authors for the drying curves.

Model no	Model name	References	Model
1	Newton	*Liu and Bakker (1997) ; O'Callaghan et al (1971)*	$MR = \exp(-kt)$
2	Page	*Agrawal and Singh (1977) ; Zhang and Litchfield (1991)*	$MR = \exp(-kt^n)$
3	Modified Page (I)	*Agrawal and Singh (1977) ; Zhang and Litchfield (1991)*	$MR = \exp[-(kt)^n]$
4	Modified Page (II)	*Diamante and Munro (1991)*	$MR = \exp[(-k(t/L^2)^n)]$
5	Henderson and Pabis	*Chhninman (1984) ; Westerman et al. (1973)*	$MR = a \exp(-kt)$
6	Wang and Singh	*Wang and Singh (1978)*	$MR = 1 + at + bt^2$

RESULTS AND DISCUSSION

The weather conditions during drying of mint, okra and grapes are shown in figure (3). During the drying experiments, the solar radiation ranged from 95 to 900 W/m^2, the air velocity from 5 to 12 m/s. The solar radiation energy is maximum at midday and minimum at evening in the day of experiment. Moreover, the temperature of ambient air ranged from 36 to 39 ^{o}c. Mean relative humidity just above surface of the plants varied between 23 % and 29 %.

Mathematical modeling of solar drying curves

In order to normalize the drying curves, the data involving dry basis moisture content versus time were transformed to a dimensionless parameter called as moisture ratio versus time.

The moisture content data at the different experimental mode were converted to the most useful moisture ratio expression and then curve fitting computations with the drying time were carried on the 6 drying models evaluated by the previous workers. The results of statistical analyses undertaken on these models for mint, okra and grapes are given in tables 2, 3 and 4, respectively and figures 4, 5 and 6. The models were evaluated based on X^2, MBE and RMSE. For mint leaves, the Modified Page (I) model was the best descriptive model (table 2). From the Modified Page (I) model for mint leaves, it was determined that X^2= $2.52x10^{-3}$, MBE=0.0188 and RMSE = 0.77611. For okra, the Newton model was the best descriptive model (Table 3). From the Newton model for okra, it was determined that X^2= $3.47x10^{-3}$, MBE= - 0.012 and RMSE = 0.051. For grapes, the Wang and Singh model was the best descriptive model as shown in table (4). From Table (4) it was determined that X^2= 1.1x10-3, MBE=-0.02823 and RMSE = 0.116417.

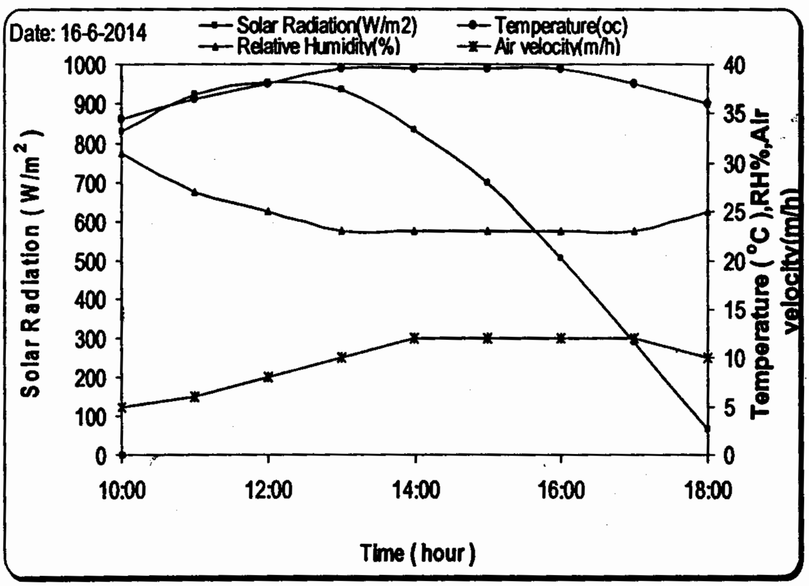


Figure (3) Weather conditions during open sun drying process in a typical experimental day.

Table 2: Modeling of moisture ratio (MR) according to the drying time of mint leaves.

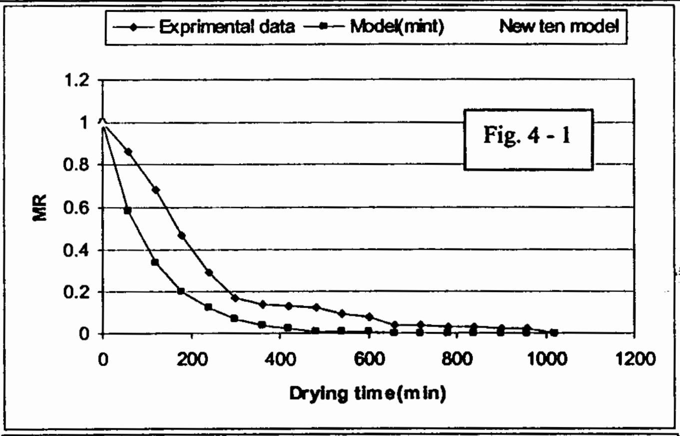
Model	Model constants	R^2	MBE	X^2	RMSE
1	k =- 0.0089	0.8262	-0.106	0.02	0.44
2	k =0.001;n =1.1433	0.9676	0.1511	0.04254	0.6233
3	k =0.004; n = 1.1433	0.9676	0.0188	2.52×10^{-3}	0.77611
4	k =0.498; n = 0.4914	0.87	$-.823\times10^{-4}$	4.6946×10^{-3}	3.68×10^{-3}
5	a = 1.0089; k = 0.0046	0.9466	-7.88x10^{-3}	1.842×10^{-3}	0.03249
6	a = -0.0026; b =0.000002	0.9444	0.1492	0.0386	0.6153

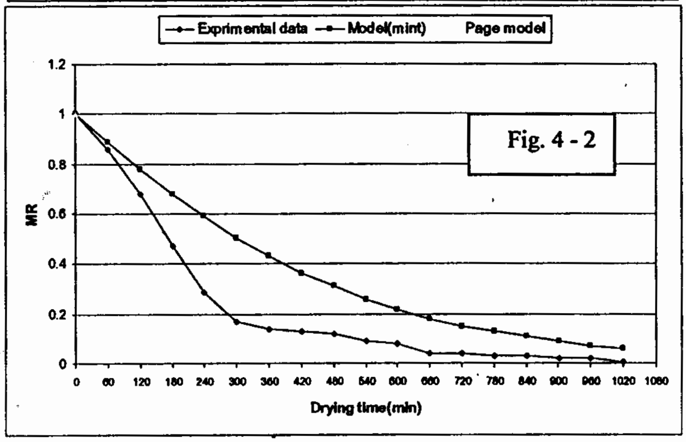
Table 3: Modeling of moisture ratio (MR) according to the drying time of okra.

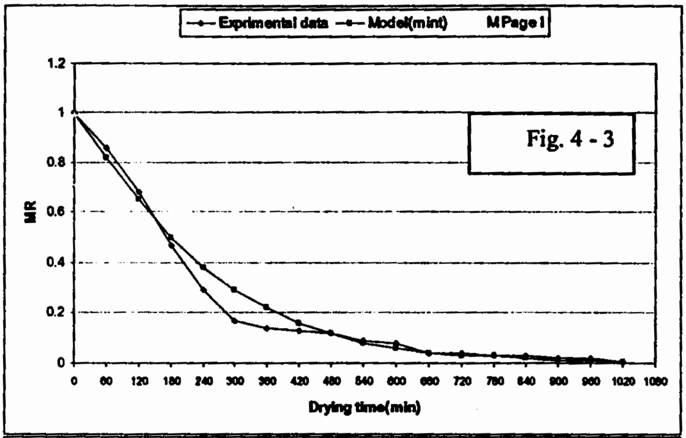
Model	Model constants	R^2	MBE	X^2	RMSE
1	k =- 0.0046	0.9689	-0.012	3.47x10^{-3}	0.051
2	k = 0.003; n = 1.0427	0.9333	0.1511	2.79x10^{-3}	0.6233
3	k = 0.004; n = 1.0427	0.9333	0.01417	2.425x10^{-3}	0.058
4	k = 0.6299; n = 0.4385	0.8034	-0.0311	0.016728	0.1283
5	a = 1.696; k = 0.0062	0.9471	0.0187	0.02458	0.07712
6	a = -0.0021; b = 0. 000001	0.9681	0.05788	0.01913	0.2386

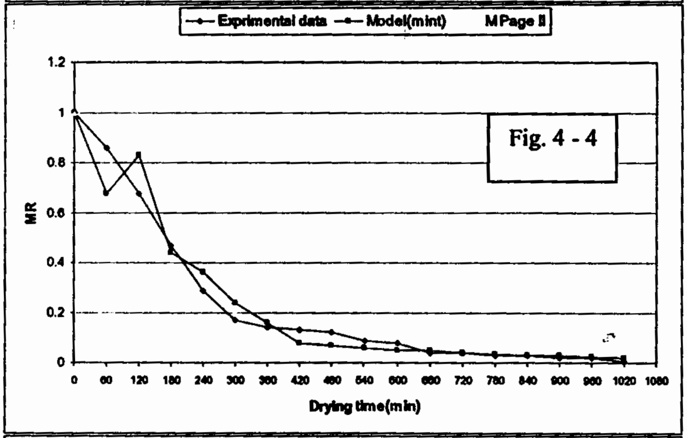
Table 4: Modeling of moisture ratio (MR) according to the drying time of grapes.

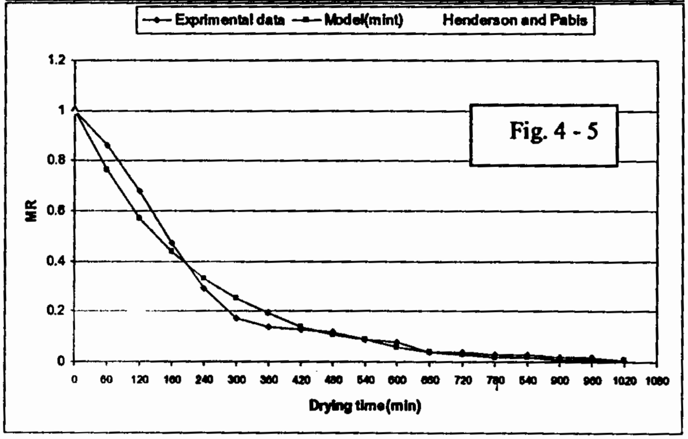
Model	Model cons.	R^2	MBE	X^2	RMSE
1	k =- 0.0035	0.8689	-0.142	0.029	0.587
2	k = 0.000009; n = .8700	0.9676	0.01288	$3.12x10^{-3}$	0.05311
3	k = 0.0006; n = 1.8703	0.9676	0.482	0.3143	1.9887
4	k = 0.0924; n = 0.784	0.8277	-0.0218	$4.8133x10^{-3}$	0.0533899
5	a = 1.5984; k = 0.0035	0.8687	$-3.52x10^{-3}$	$5.746x10^{-3}$	0.01455
6	a = -0.0018; b = 0.00008	0.9883	-0.02823	$1.1x10^{-3}$	0.116417






Exprimental data
Model(mint)
MPage I
Fig. 4 - 3
MR
1.2
1
0.8
0.6
0.4
0.2
0
0
60
120
180
240
300
360
420
480
540
600
660
720
780
840
900
960
1020
1080
Drying time(min)


Exprimental data
Model(mint)
MPage II
Fig. 4 - 4
MR
1.2
1
0.8
0.6
0.4
0.2
0
0
60
120
180
240
300
360
420
480
540
600
660
720
780
840
900
960
1020
1080
Drying time(min)


Exprimental data
Model(mint)
Henderson and Pabis
Fig. 4 - 5
MR
1.2
1
0.8
0.6
0.4
0.2
0
0
60
120
180
240
300
360
420
480
540
600
660
720
780
840
900
960
1020
1080
Drying time(min)

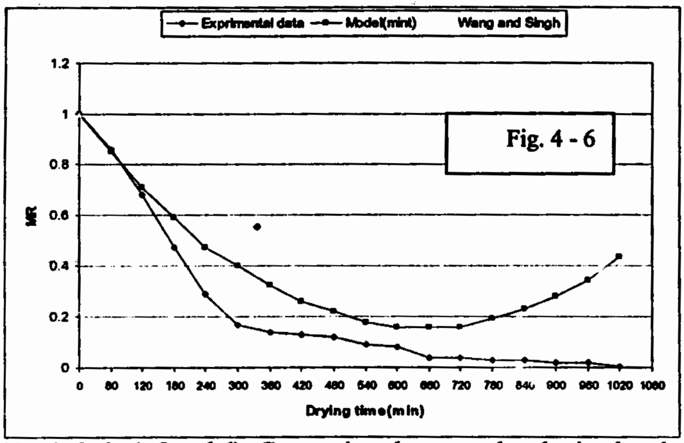
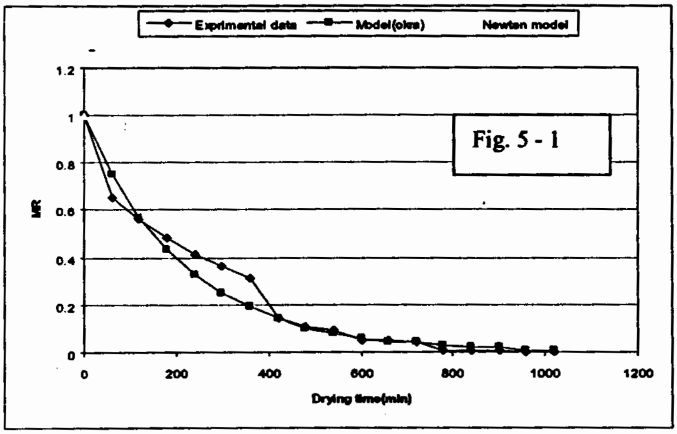
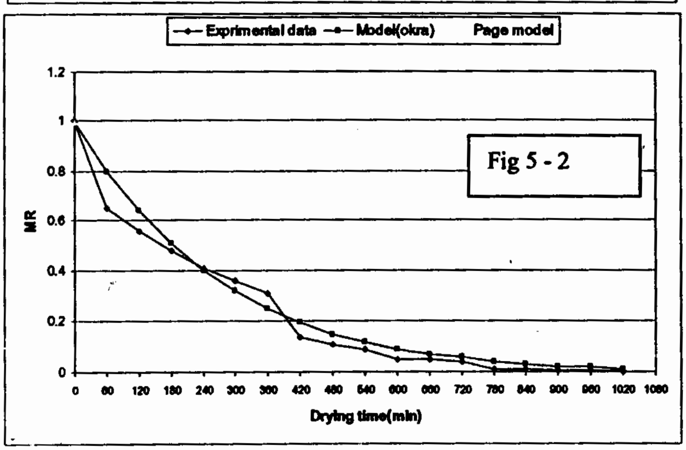


Figure (4 – 1, 2, 3, 4, 5 and 6); Comparison between the obtained and calculated (MR), which calculated from the tested models for mint.





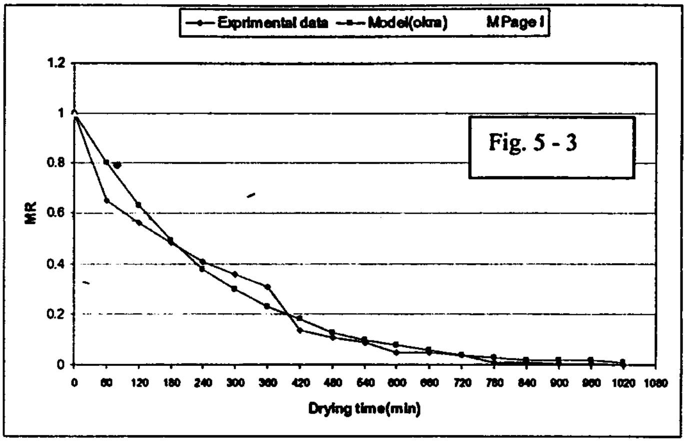


Fig. 5 - 3

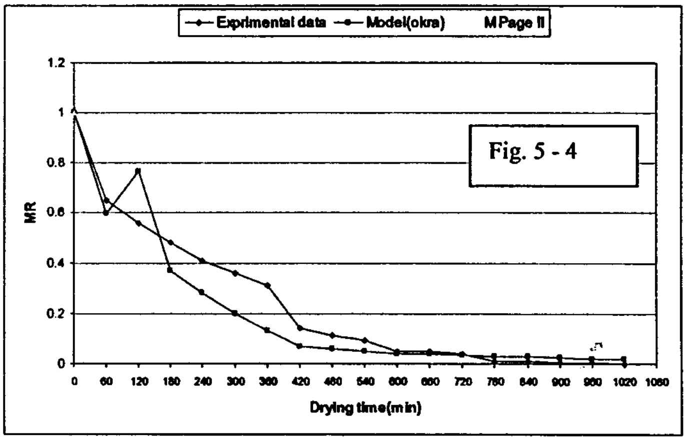


Fig. 5 - 4

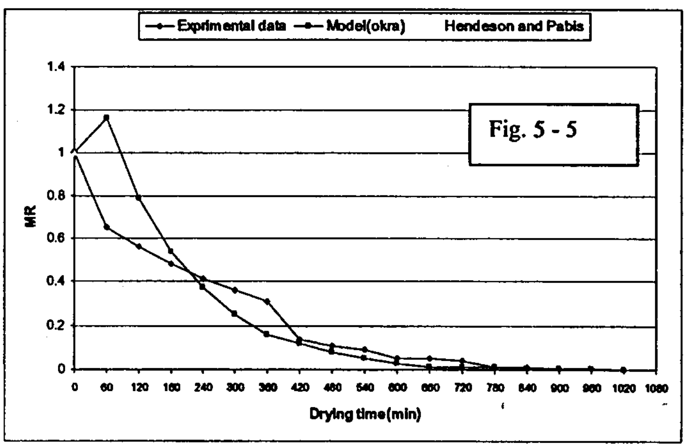


Fig. 5 - 5

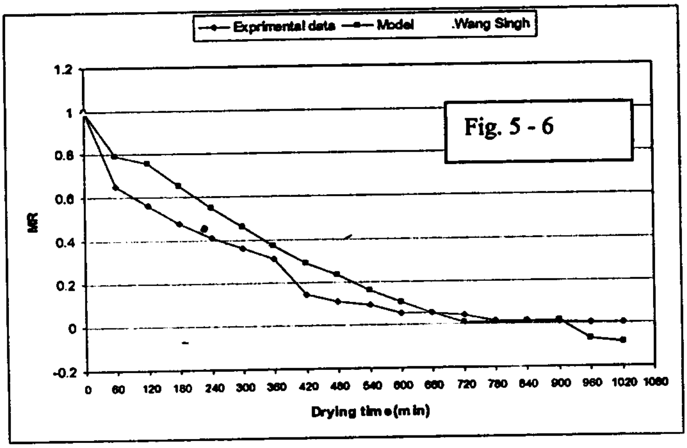
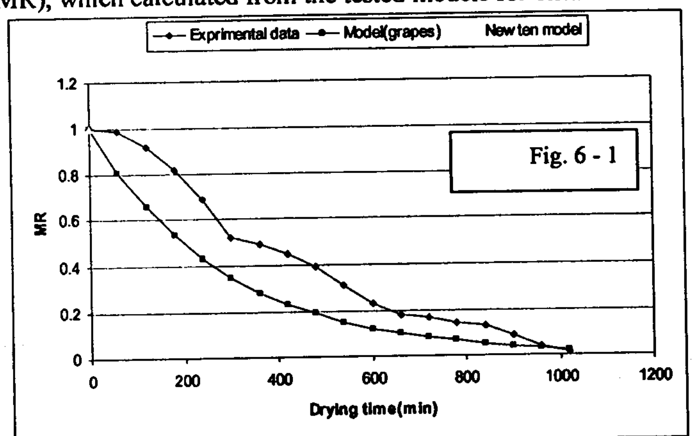
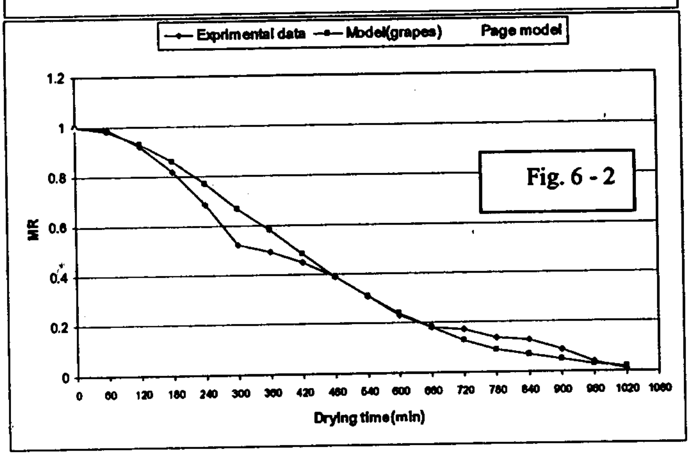


Figure (5– 1, 2, 3, 4, 5 and 6): Comparison between the obtained and calculated (MR), which calculated from the tested models for okra.





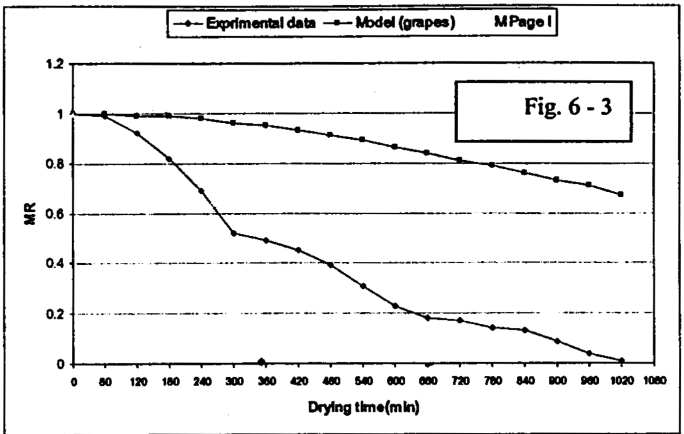


Fig. 6 - 3

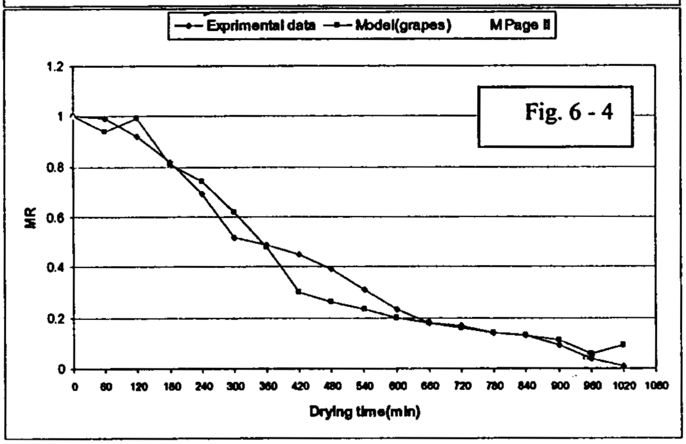


Fig. 6 - 4

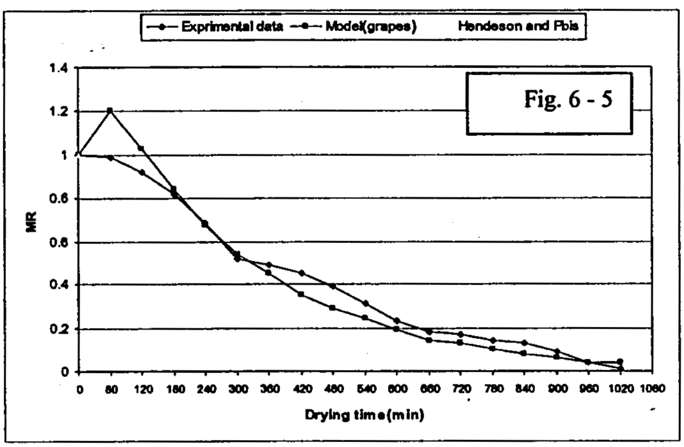


Fig. 6 - 5

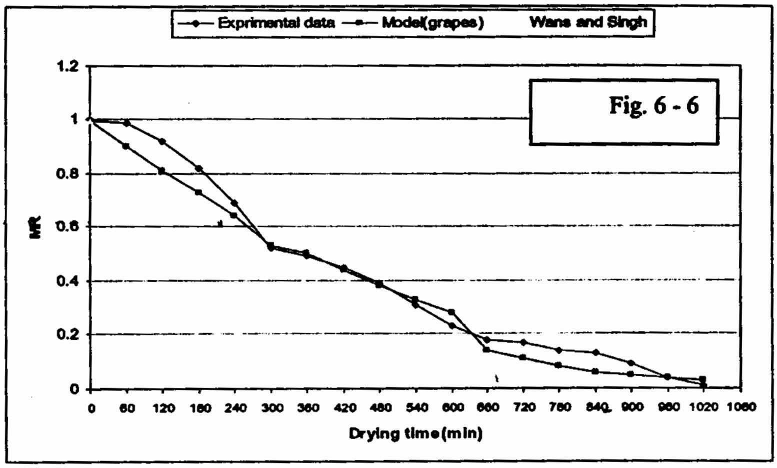


Figure (6 – 1, 2, 3, 4, 5 and 6): Comparison between the obtained and calculated (MR), which calculated from the tested models for graves.

CONCLUSIONS

The drying behavior of mint, okra and grapes were investigated under solar draying mode. During the drying experiments, the solar radiation ranged from 95 to 900 W/m^2, the air velocity from 5 to 12 m/s. The solar radiation energy is maximum at midday and minimum at evening in the day of experiment. Moreover, the temperature of ambient air ranged from 36 to 39 C^o. Mean relative humidity just above surface of the plants varied between 23 % and 29 %.To explain the drying behavior of mint, okra and grapes 6 thin-layer drying models were applied. The drying data were fitted to six different mathematical models. Among the models. The models were evaluated based on X^2,MBE and RMSE. For mint leaves, the Modified Page (I) model was the best descriptive model, it was determined that X^2= 2.52x10^{-3}, MBE=0.0188 and RMSE = 0.77611. For okra, the Newton model was the best descriptive model, it was determined that X^2= 3.47x10^{-3}, MBE=-0.012 and RMSE = 0.051. For grapes, the Wang and Singh model was the best descriptive model ,it was determined that X^2= 1.1x10-3, MBE=-0.02823 and RMSE = 0.116417.

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الملخص العربي

دراسة اداء مجفف شمسى لبعض المحاصيل (النعناع والعنب والبامية)
II- توافق سلوك التجفيف الشمسى مع النماذج الرياضية للتجفيف في طبقات رقيقة

منى محمود عبد العزيز حسن*

تهدف الدراسة إلى مقارنة سلوك التجفيف لشرائح بعض المحاصيل مثل النعناع و البامية و العنب فى طبقات رقيقة تحت ظروف التجفيف فى مجفف شمسى مباشر بالحمل الطبيعى مع ستة نماذج رياضية.

وكانت النتائج كالتالى:

١- كانت اعلى درجة حرارة داخل غرفة المجفف ٦٦ درجة مئوية عندما كانت درجة الحرارة البيئية والرطوبة النسبية المقابلة 36 الى ٣٩ درجة مئوية و٢٣ الى ٢٩ % على التوالي وكانت سرعة الهواء ٥ الى ١٢ م/ث.

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٢- بعض المعـادلات أمكنهـا وصـف سـلوك التجفيـف الشـرائح بشـكل مرضـي تحـت ظـروف التجفيف المباشر بالحمل الطبيعى مع المجفف المستخدم فى الدراسـة وكـان ذلك مصـحوبا بقيم عاليه لمعامل الارتباط (R^2) .

حيث تنبأت معادلة بيج المعدلة بالتغير في المحتوي الرطوبي بشكل أكثر ملائمـة بالمقارنـة بالمعادلات الأخرى بالنسبة للنعناع حيث كان

$$(X^2= 2.52x10^{-3}, MBE=0.0188 \text{ and } RMSE = 0.77611)$$

وتنبأت معادلة نيوتن المعدلة بـالتغير فـي المحتوي الرطـوبي بشـكل أكثر ملائمـة بالمقارنـة بالمعادلات الأخرى بالنسبة للبامية حيث كان

$$(X^2= 3.47x10^{-3}, MBE=-0.012 \text{ and } RMSE = 0.051)$$

وتنبأت معادلة وينج و سنج المعدلة بالتغير في المحتوي الرطوبي بشكل أكثر ملائمـة بالمقارنة بالمعادلات الأخرى بالنسبة للعنب حيث كان

$$(X^2= 1.1x10\text{-}3, MBE=-0.02823 \text{ and } RMSE = 0.116417)$$